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THE MICROMORPHOLOGY OF GYPSUM AND HALITE IN REG SOILS—THE NEGEV DESERT, ISRAEL

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ABSTRACT

Gypsum and halite are the most common salts in reg soils developed on alluvial parent material under extremely arid conditions in the Negev Desert, Israel. The aim of this paper is to document the changes in the micromorphology of these salts at different stages of Reg soil development on two alluvial fan chronosequences. The micromorphological analyses included thin section observations and scanning electron microscope and electron microprobe analyses.

In this arid soil environment, gypsum and halite possess a variety of crystal forms which may change with depth in a single profile and/or between profiles of different ages. The variety of crystal forms results from changes in the microenvironmental conditions that occur in desert reg soils over time. Poikilitic lenticular gypsum is found in all Reg soils and is distributed throughout the profiles. The conditions needed for such crystals to form are high ionic impurities and deposition in a void system where space is not limiting. Microcrystalline alabastrine gypsum is only found in mature Reg soils and is crystallized when the profile has high amounts of fine material and a well-developed desert pavement. In a well-developed Reg soil, profile indicators, such as a well-developed desert pavement and high amounts of fine earth, limit the leaching depth and cause gypsum deposition from supersaturated soil solutions under high evaporation rates close to the surface. Prismatic and fibrous gypsum are less common. Low amounts of prismatic gypsum are found in young and mature soils while fibrous gypsum is found only in mature soils in re-cemented shattered gravel.

The halite crystal form is mainly cubic with low amounts of host material incorporated into the crystal. It occurs predominantly in mature Reg soil profiles through the crystallization from supersaturated soil solutions at the depth of maximum water penetration. Although the alabastrine, prismatic and fibrous gypsum and cubic halite are deposited in a displacive manner, no correlation was found between their occurrence and the distribution of shattered gravel in the soil profile.

KEY WORDS Reg soil; salts; crystal form; gypsum; halite; shattered gravel; micromorphology; Negev; Israel

INTRODUCTION

Gypsum and halite are very common salts in Aridisols, saline and alkaline soils, Sulfaquepts and irrigated soils (Eswaran *et al.*, 1980; Eswaran and Gong, 1991). Gypsum occurs in several different crystal forms such as lenticular, microcrystalline, prismatic and fibrous. Lenticular gypsum appears as single intercalary crystals, continuous coatings or infillings, while microcrystalline gypsum is powdery and smooth with crystals less than 20 μm in size. Both the prismatic and the fibrous gypsum crystal forms are less common in soils (Barazanji and Stoops, 1974; Porta and Herrero, 1990; Eswaran and Gong, 1991; Jafarzadeh and Burnham, 1992). Halite in soils can also have a variety of forms such as fibrous, cubic, trigonal pyramids and diffuse continuous waxy coatings on void walls and aggregates (Eswaran *et al.*, 1980). The most common forms of halite in soils are the cubic crystals and the diffuse waxy coating.

These salts and their crystal forms are commonly found in soils which were affected by a high water table, developed on gypsiferous parent material or in fine parent material (Barazanji and Stoops, 1974; Eswaran

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et al., 1980; Mees and Stoops, 1991). Few studies however, have described the micromorphology of gypsum and halite in dry, well-drained soils on non-salic or gypsic parent materials.

Reg soils are desert soils developed on coarse, well-drained, gravelly alluvial parent material. They are found in all deserts. In the hyperarid parts of the Negev Desert, Israel, these soils are pedogenically characterized by desert pavement, a vesicular A horizon, high amounts of soluble salts, mainly halite and gypsum, salt-shattered gravel in the B and C horizons, and the development of gypsic and sometimes petrosalic horizons (Dan *et al.*, 1982; Amit and Gerson, 1986; Gerson and Amit, 1987). Five stages of Reg soil development have been defined (Amit *et al.*, 1993), and the nature of the salt deposits was one of the main pedogenic indicators used. A wide variety of forms of gypsum and halite were described in these soils.

The primary aim of this paper is to document the changes in the micromorphology of the salts at different stages of Reg soil development. A second objective is to determine if a relationship exists between crystal form and the gravel-shattering process.

STUDY SITES

Two study sites were chosen: the chronosequence of Nahal (wadi) Ze'elim alluvial fan surfaces, along the Dead Sea coast, and the chronosequence of the Nahal Shehoret alluvial fan in the southern Arava Valley (Figure 1). The Ze'elim chronosequence is of Holocene age starting some 14 000 years ago (Begin *et al.*,

Figure 1. Location map, southern Israel, with the two study sites, Ze'elim fan and Shehoret fan

1985). The alluvial fan of Nahal Shehoret is located in the southern Arava Valley and consists of five groups of surfaces dated Pliocene to Holocene (Gerson *et al.*, 1993). Nine Reg profiles were selected (out of 74 analysed soil profiles) for micromorphological analyses. Seven were young Reg soils of Holocene age from the Ze'elim site and two were mature profiles of Pleistocene age from the Shehoret alluvial fan (Table I).

The present climate in the study area is extremely arid: 30–60 $mm a^{-1}$ of rainfall with a high interannual variability. Mean annual temperature is 25°C with a mean of 30°C for August and 15°C for January. Potential evaporation is high, 2200–2600 $mm a^{-1}$, and the mean annual humidity is low 45–50 per cent (Atlas of Israel, 1985). The vegetation cover on the Holocene surfaces is very sparse (less than 5 per cent) and characterized mainly by annuals, with some perennials such as *Hammada salicornica*, *Anabasis setifera* and *Zygophyllum dumosum*. On the Pleistocene to Pliocene surfaces, because of extremely high salt concentrations, the vegetation is virtually absent.

FIELD AND LABORATORY METHODS

Preparing thin sections of gravelly soils while preserving the salts presented several difficulties. The gravelly parent material and the shattered gravel are very coarse and loose and thus conventional soil-sampling methods are not effective for these soils. In order to preserve the salts deposited around clasts and inside shattered gravel, each of the sampled clasts (varying from 5 to 20 cm in size) was wrapped tightly in the field with soft paper and 'masking tape'. These samples were later impregnated in the laboratory. In order to preserve the salts in the loose soil matrix, soil blocks, $20 \times 30 \times 40$ cm in size, were dug and isolated. Liquid wax was then poured on top of these isolated blocks. When cooled, the block was removed thus preserving the structural integrity of the gravelly soil sample. Only the inner part of the block, which was unaffected by the wax, was used for the micromorphological analysis.

The standard method of impregnating samples for thin section analysis involves either heating the impregnating material or placing the sample under high vacuum. This procedure would destroy the salt cutans and cause loss of the original structure of the shattered gravel and the soil matrix. Instead, a mixture of polyester (555 Phyberplast), hardener (Butanox M-60) and thinner (Styrene), was introduced to the gravel under low vacuum. This treatment resulted in perfect penetration of the polyester into the samples while at the same time preserving the salt cutans inside the shattered loose gravel cracks and the original shape of the shattered gravel. The impregnated samples were dried under room temperature. Thin sections were cut using oil (Parasol) instead of water for cooling, in order not to dissolve the salts.

Thin section observations and micromorphological descriptions of the salts were made using petrographic and scanning electron microscopy (SEM) and electron microprobe. The descriptions of the thin sections were based on the terminology of Brewer (1964) and of Bullock *et al.* (1985). Forty thin sections were analysed: 20 were of 3×5 cm in size and 30 μm thick, and 20 were 4×8 cm in size and 30 μm thick.

The SEM and the electron microprobe analyses were carried out using carbon-coated stubs (1×1 cm in size and 0·5 cm thick) prepared from the impregnated samples in order to analyse the salts inside cracks and microcracks of the shattered gravel. This method enabled us to analyse the two crack planes in the shattered gravel and to determine the relations between the crack planes and the distribution of the different salts within. Special attention was paid to the crystal forms of the different salts and to the relations between the shattered fragments and the salt crystals inside the analysed cracks. Fresh samples were analysed only from the well-indurated petrosalic horizon.

The soil profiles were also described and sampled by standard pedological methods (Dan *et al.* 1964; Birkeland, 1984). They were classified using the U.S. Soil Taxonomy (Soil Survey Staff, 1975; ICOMID, 1989) and sampled during the dry summer. Laboratory work included both chemical and granulometric analyses of the soil horizons. Electrical conductivity was measured in a 1 : 1 extract. Concentrations of Na^+, K^+, Ca^{2+}, Mg^{2+} were measured by atomic absorption. The anions Cl^- and SO_4^{2-} were measured by ion chromatography. Gypsum content was determined using the Schleiff method (Schleiff, 1979). Mineralogical analysis of salt cutans coating gravel surfaces and salt cutans found inside cracks of shattered gravel and inside the non-shattered gravel were made by X-ray diffraction analysis (using Phillips P.W. 1730 with Cu radiation) and binocular screening.

Table I. Some physico-chemical micromorphological characteristics of Reg soil profiles, Nahal Ze'elim and Nahal Shehoret alluvial fans (after Amit *et al.*, 1993)

Profile no.	Site	Classification	Age pedomorphic surface	Petrography of parent material	Desert pavement evolution, A_0*	Horizon	Depth (cm)	Silt (%)	Clay (%)	Salinity EC† (mmho/cm)	Gypsum meq/100 g soil	Salt mineralogy‡ Gypsum	Halite	Anhydrite	Shattered gravel (%)	Micromorphological characteristics of salt cutans in shattered gravel cracks§	Stage of gravel shattering¶
1	Ze'elim-15	Floodplain sediment	Late Holocene	Gravel composed of limestone, dolomite and chert	None	Sediment	0–2	1·4	2·5	0·31	0·00	–	*		None		A
						Sediment	2–50	2·1	1·5	0·22	0·00	–	*		None		
2	Ze'elim-14	Torrifluvent	Late Holocene	Gravel composed of limestone, dolomite and chert	None	A	0–2	16·1	12·7	0·98	0·33	–	–		None	Poikilitic lenticular gypsum crystals, 0·25–0·50 mm diameter; Displacive prismatic gypsum crystal, 0·25–0·50 mm and/or 1–4 mm diamater; Displacive halite cubes, 1–50 μm diameter	B
						C	2–50	8·2	2·1	3·49	1·27	****	*		None		
						Sediment	50+	–	–	–	–	–	–		None		
3	Ze'elim-13	Torrifluvent	Holocene	Gravel composed of limestone, dolomite and chert	None	A	0–0·5	9·1	9·0	0·98	0·71	–	–		None	Poikilitic lenticular gypsum crustals, 0·25-0·50 mm diameter; Displacive prismatic gypsum crystal; 0·25–0·50 mm and/or 1–4 mm diameter; Displacive halite cubes, 1–50μm diameter	B
						C	0·5–40	5·5	4·1	0·62	1·90	****	*		None		
						Sediment	40+	–	–	–	–	–	–		None		
4	Ze'elim-12	Torrifluvent	Holocene	Gravel composed of limestone, dolomite and chert	Low	Av	0–0·5	61·3	14·7	14·63	0·73	–	–		None	Poikilitic lenticular gypsum crystals, 0·25–0·50 mm diameter; Displacive prismatic gypsum crustal, 0·25–0·50 mm and/or 1–4 mm diameter, Displacive halite cubes, 1–50 μm diameter	C
						B	0·15–1·5	60·0	14·7	12·06	2·44	–	–		None		
						C	1·5–43	36·3	3·0	10·46	4·41	****	**		15–20		
						Sediment	43+	20·8	1·9	10·35	4·20	–	–		None		
5	Ze'elim-11	Torrifluvent	Middle Holocene	Gravel composed of limestone, dolomite and chert	Low	Av	0–0·5	49·3	18·2	4·25	0·39	–	**		None	Poikilitic lenticular crystals, 0·35–0·50 mm diameter; Displacive prismatic gypsum crystal, 0·25–0·50 mm and/or 1–4 mm diameter; Displacive halite cubes, 1–50 μm diameter	C
						B	0·5–6·5	39·2	1·8	2·63	3·83	–	–		None		
						C	6·5–45	29·8	2·0	8·01	14·75	****	**		20		
						Sediment	45+	–	–	–	–	–	–		None		
6	Ze'elim-2	Typic Haplogypsid	Early Holocene	Gravel composed of limestone, dolomite and chert	Medium	Av	0–0·5	23·6	5·9	9·41	0·54	–	–		None	Poikilitic lenticular gypsum crystals, 00·25 mm–0·50 mm diameter; Displacive prismatic gypsum crystal, 0·25–0·50 mm and/or 1–4 mm diameter; Displacive halite cubes, 1–50 μm diameter	D
						Bg. f.	0·5–1·5	19·0	5·1	17·88	0·96	–	–		None		
						C1	1·5–15	29·8	3·0	20·70	1·37	****	–		70		
						C1	15–20	45·8	17·8	26·35	2·24	****	***		None		
						C1	20–30	43·1	12·1	23·53	12·18	****	**		None		
						C2	30–40	16·7	1·5	18·82							
						C2	40–50	42·0	7·1	18·88	15·59	****	**		15		
						Sediment	50–70	69·3	15·2	7·78	33·68	****	*		None		
											80·42	****	●		None		
7	Ze'elim-1	Typic Haplogypsid	Early Holocene	Gravel composed of limestone, dolomite and chert	Medium	Av	0–0·5	18·0	3·9	15·99	2·81	–	–		None	Poikilitic lenitular gypsum crystals, 0·25–0·50 mm diameter; Displacive prismatic gypsum crystals, 0·25–0·50 mm and/or 1–4 mm diameter; Displacive halite cubes, 1–50 μm diameter	D
						Bg. f.	0·5–1·5	29·7	3·3	10·35	2·46	–	–		None		
						C1	1·5–30	17·0	2·3	17·88	14·47	****	***		70		
						C2	30–55	69·6	12·3	18·82	87·03	****	**		15		
						Sediment	55–80	25·3	7·6	10·24	34·31	****	**		None		
8	Shehoret-3	Gypsic Haplosalid	Middle Pleistocene	Gravel composed of limestone, chert, sandstone, igneous rocks, granite, schist, diorite	High	Av	0–0·5					–	–		None	10–35 cm depth; displacive alabastrine gypsum; Poikilitic lenticular gypsum crystals, 0·25–0·5 mm; Displacive prismatic gypsum crystals, 0·25–0·54 and 1–4 mm; Displacive firous gypsum crystals, 0·25 mm length; Displacive halite cubes, 1–50 μm diameter. 35–45 cm depth; Poikilitic lenticular gypsum crystals, 0·25–0·55 mm diameter; Displacive prismatic gypsum crystals, 0·25–0·5 to 1–4 mm; Displacive fibrous gypsum crystals, 0·25 mm length Displacive halite cubes, 1–50 mm diameter. 50–100 cm depth: Polkolitic lenticular gypsum crystals, 0·25–0·5 mm diameter; Displacive prismatic gypsum crystals; Displacive halite cubes, 1–50 μm diameter;	E
						Bg. f.	0·5–8·5	45·4	6·8	16·94	1·67	**	*		None		
						B2cs	8·5–20	40·7	1·6	28·80	335·76	****	●	***	80		
						C1cs,sa	20–28	7·2	1·3	21·08	129·61	**	*		10		
						C2cs,sa	28–44	9·8	1·7	31·25	49·90	**	*		1		
						C3sa	44–70	9·9	2·3	225·88							
						C4sa	70–80	18·9	5·0	210·83							
						Sediment	80–85	7·3	3·3	14·12							
											27·20	**	****		None		
											135·33	*	****		None		
											12·48	*	***		None		

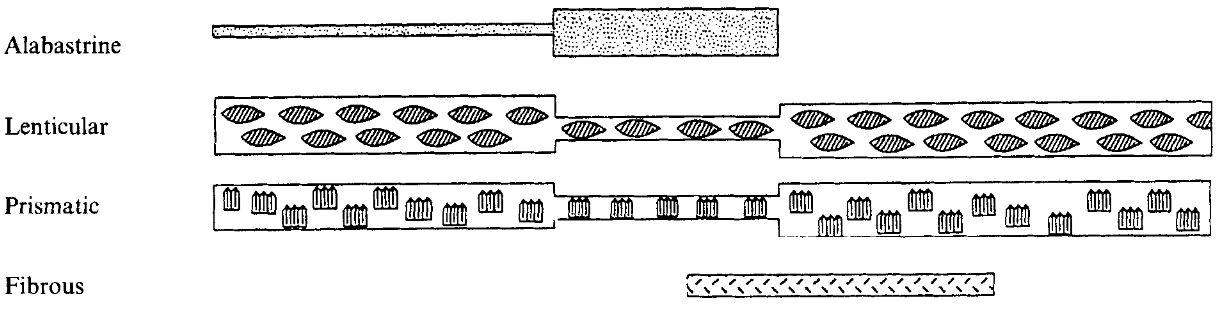
Table I. (Continued)

Profile no.	Site	Classification	Age pedomorphic surface	Petrography of parent material	Desert pavement evolution, A_0*	Horizon	Depth (cm)	Silt (%)	Clay (%)	Salinity EC† (mmho/cm)	Gypsum meq/100 g soil	Salt mineralogy‡ Gypsum	Halite	Anhydrite	Shattered gravel (%)	Micromorphological characteristics of salt cutans in shattered gravel cracks§	Stage of gravel shattering¶
9	Shehoret-1	Gypsic Haplosalid	Upper Pleistocene	Gravel composed of limestone, chert, sandstone igneous rocks, granite, schist, diorite	High	Av.	0–0·5	42·8	7·3	22·08	2·28	–	–		None	10–35 cm depth; Displacive alabastrine gypsum; Poikilitic lenticular gypsum crystals; 0·25–0·5 mm; Displacive prismatic gypsum crystals, 0·25–0·5 and 1–4 mm; Displacive fibrous gypsum crystals; 01·25 mm length; Displacive halite cubes, 1–50 μg diameter. 35–45 cm depth: Poikilitic lenticular gypsum crystals, 0·25–0·5 mm diameter; Displacive prismatic gypsum crystals, 0·25–0·5 or 1–4 mm; Displacive fibrous gypsum crystals, 0·25 mm length; Displacive halite cubes, 1–50 mm diameter. 50–100 cm depth; Poikilitic lenticular gypsum crystals, 0·25–0·5 mm diameter; Displacive prismatic gypsum crystals; Displacive halite cubes, 1–50 μm diameter	
						Bg. f.	0·5–15	44·2	7·1	18·82	262·46	****	*		None		
						B2cs	15–30	8·3	1·2	34·38	536·70	****	**	***	85		E
						C1cs,sa	30–55	10·9	2·2	70·57	164·17	***	***		50		
						C2sa	55–80	15·7	1·4	165·65	16·97	***	***		None		
						C3sa	80–90	8·5	0·6	8·69							
						Sediment	90–120	4·0	1·0	7·81							
											38·00	***	****		None		
											6·86		–		None		

* For degree of desert pavement evolution, see Amit and Gerson (1986)
† $mmho\,cm^{-1} \times 0{\cdot}1 = Sm^{-1}$
‡ * rare ** low *** frequent **** very frequent
§ detail on the micromorphology of gypsum and halite cutans is in the text.
¶ For definition of development see Figure 8, and results.

Table II. Distribution of gypsum crystal forms in young and mature Reg soils (width of band indicates relative frequency)

		Mature Reg soils (Stage E)		
Horizons Gypsum crystals	Young reg soil (Stage A–D)	Gypsum horizon B2 cs, 10–35 cm	C horizons, 35–45 cm	Petrosalic horizon without shattered gravel, 50–100 cm



RESULTS

Gypsum and halite crystal forms in Reg soil profiles

Gypsum and halite were crystallized in the Reg soils in a variety of crystal forms. Some of the soils displayed all of the various forms while others contained only part of them (Table II). Four different crystal forms of gypsum were identified:

1. *Alabastrine gypsum*. This is microcrystalline gypsum, white in colour, soft and smooth like flour, 5–20 μm in size (Figure 2). This type of gypsum crystallizes in a displacive way, either displacing the host soil material or the shattered fragments inside the cracks of shattered gravel (Figure 3).

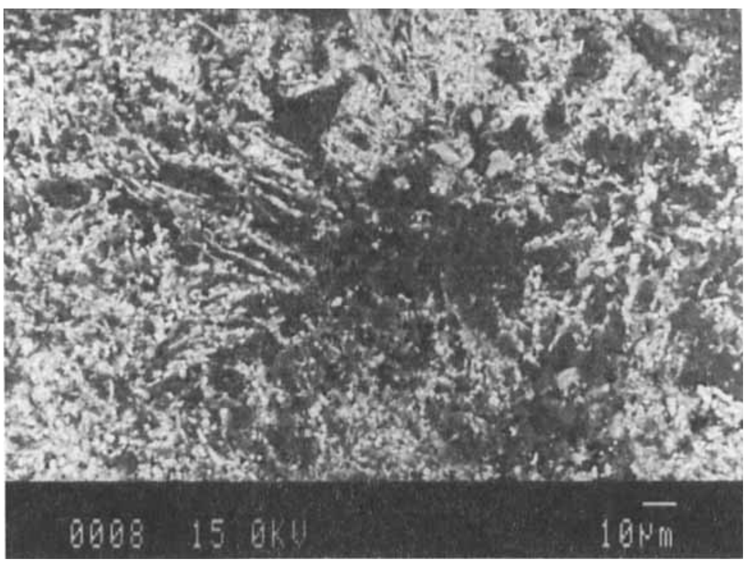


Figure 2. Alabastrine gypsum displacing host material at B2cs horizon in mature Reg soil, profile 9, 15–30 cm depth (electron microprobe)

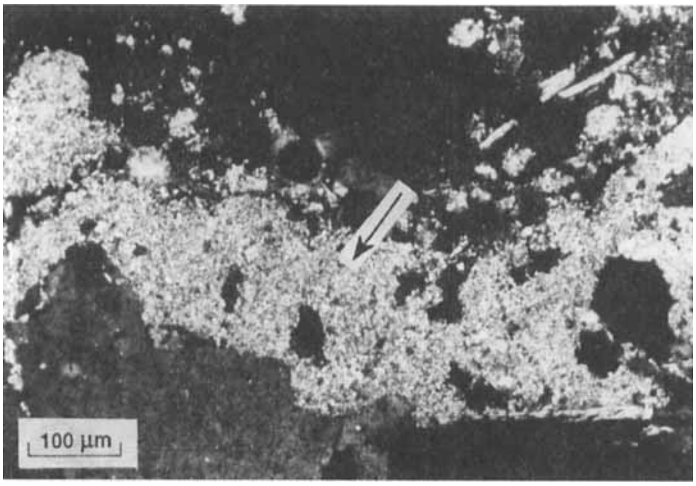


Figure 3. Alabastrine gypsum deposited in contact with crack margin displacing soil matrix (Table I, profile 9, B2cs horizon, 15–30 cm depth) (XPL, crossed polarizers)

2. *Lenticular gypsum*. The size of the gypsum lenses ranges from 0·25 to 0·5 mm. They are anhedral to subhedral in shape and poikilitic in nature (Figure 4). They were crystalized in a passive way and include grains from the soil matrix. The lenticular gypsum has no preferred orientation and was found in the soil matrix and inside cracks.
3. *Prismatic gypsum*. The gypsic prisms are euhedral and they crystallizes perpendicularly to the plane of fracture, shattered fragments or gravel surfaces (Figure 5a,b). They range from 0·25 to 0·5 mm in size. Crystallization is displacive and no grains of the soil matrix were found in the crystal.
4. *Fibrous gypsum crystals*. The fibrous gypsum crystallizes in the shape of thin needles/fibres with a mean length of 0·25 mm. They crystallize in all directions displacing soil matrix or shattered gravel fragments.

Halite in the Reg soils has two distinct forms:

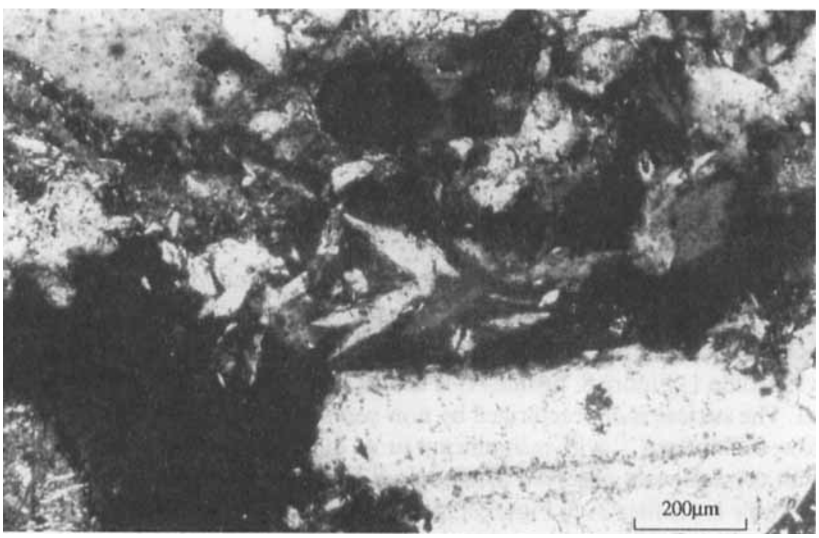


Figure 4. Lenticular gypsum with no preferred orientation (Table I, profile 7) (XPL)

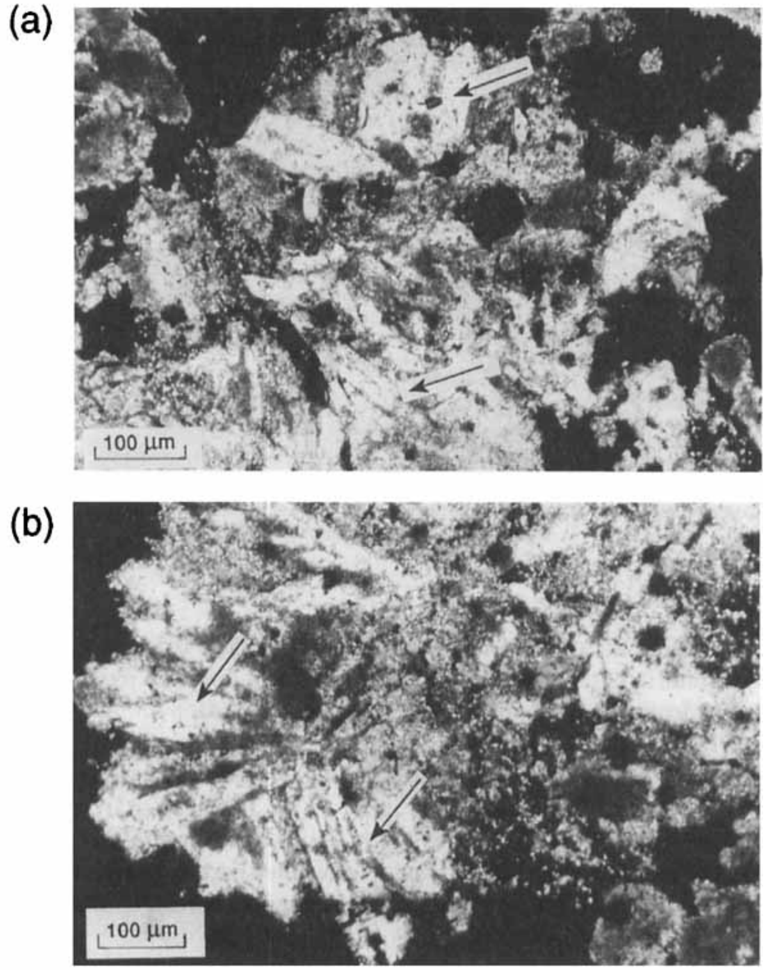


Figure 5. (a, b). Prismatic gypsum crystals displacing soil matrix including shattered gravel fragments (Table I, profile 7) (XPL)

1. *Discontinuous halite crystallization.* Discontinuous halite crystallizes as cubic crystals in the soil matrix. The subhedral halite cubes (1–50 μm) include grains from the soil matrix and have no preferred orientation.
2. *Continuous halans.* Continuous cutans attach to grains, gravel and crack surfaces with almost no host material (Figure 6a,b). These halans are composed of euhedral cubic crystals (1–50 μm) and have a preferred orientation. Such halite cutans displaced the soil matrix while it grew on the gravel surface or displaced the shattered fragments inside cracks during the process of crystallization (Figure 7).

Pedofeatures and micromorphology of salts in relation to stages of development of Reg soils

Each stage of Reg soil development is characterized by a distinct assemblage of gypsic and halite crystal forms and a specific distribution of the salts with depth.

Stage A (Table I, profile 1; Figure 8, profile A) is found on young alluvial surfaces recently abandoned by the stream channel. The surface is characterized by non-weathered bar and swale topography. Mean salinity of the soil is very low, 0·27 mS cm^{-1}, with insignificant or no gypsum. The mean percentage of fine soil material is 4 per cent. No salt crystals were observed around and inside gravel at this stage.

Stages B and *C* (Table I, profiles 2–5; Figure 8, profiles B,C) are Torrifluvents with AC profiles; they were developed on young, stable alluvial surfaces of Holocene age. The surface has bar and swale topography with no desert pavement. The salinity is low, ranging from 0·23 to 10 mS cm^{-1}, and gypsum reaches a maximum

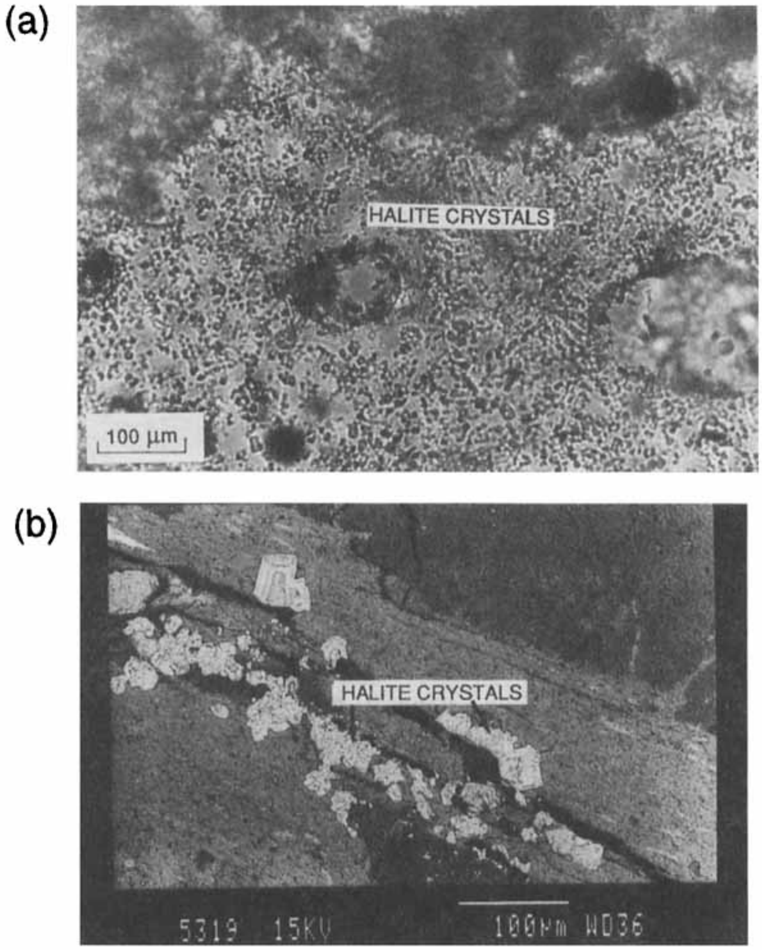


Figure 6. (a) Halite cutan envelope gravel surface with no host material (Table I, profile 10, B2cs, 15–30 cm depth) (PPL, plain light). (b) Halite crystals along crack in shattered granite gravel (Table I, profile 10, B2cs, 15–30 cm depth) (SEM)

value of 5 per cent. Most of the salts are dispersed throughout the profile but some form discontinuous cutans on the underside of clasts or in the cracks of the shattered gravel. The cutans are either gypsic or halitic. Gypsum composing the salt cutans is poikilitic lenticular and the halite is deposited as euhedral cubic crystals which are non-poikilitic. Salts in shattered gravel were found at stage C (15–20 per cent) and distributed from the surface to a depth of 45 cm. The profiles are very permeable and have incipient horizon development.

Reg soils of *stage D* (Table I, profiles 6, 7; Figure 8, profile D) are Typic Haplogypsids, and defined as mature Holocene Reg soils. The surface is characterized by bar and swale topography and a moderately developed desert pavement (A_0 horizon) covers 50 per cent of the surface. The profiles have a silty Av (i.e. vesicular) horizon, with a cambic B and a gravelly C horizon which occupies most of the soil profile. The C horizon contains high amounts of salts, in particular gypsum. Salt is dispersed throughout the soil profile. The mean EC value in these profiles is 16 mS cm^{-1} with 4 per cent gypsum. The mean percentage of fine earth is 42 per cent. There is the beginning of halite accumulation in the soil but the gypsum concentrations are still dominant (Figure 4, and Table I, Ze'elim 1, 2). The salt cutans found in the cracks of shattered gravel have a discontinuous nature; they are composed mainly of gypsum. The shape of the gypsum crystals in the crack filling and around the gravel is mainly poikilitic lenticular with no preferred orientation. In addition, at this stage, euhedral gypsum prisms of 0·25–0·5 mm size were crystallized perpendicular to the crack planes and the gravel and grain surfaces displacing the host material (Figure 5).

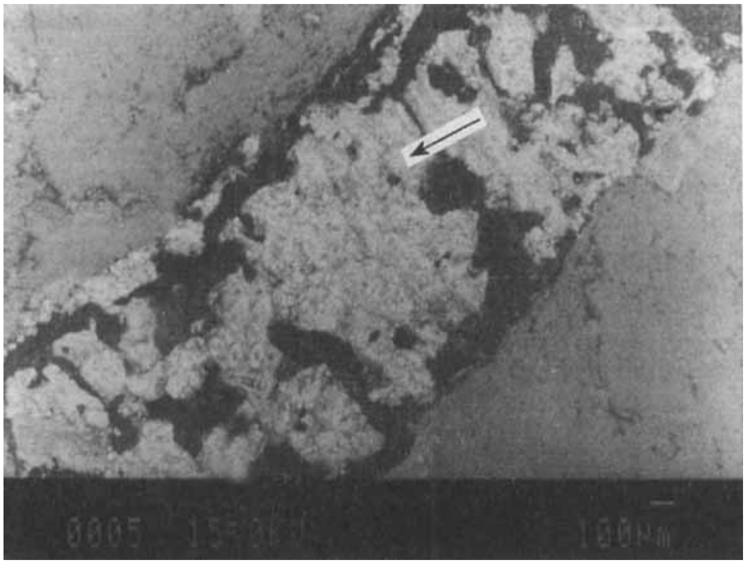


Figure 7. Halite displacing shattered gravel fragments (Table I, profile 10, B2cs, 15–30 cm depth) (electron microprobe)

Halite accumulations were occasionally found alongside the gypsum. The halite is deposited as euhedral cubes attached to the grains and gravel surfaces with almost no host material. The shattered gravel is distributed from the surface to a mean depth of 40 cm. There is no displacement of the shattered fragments in the soil horizons and the shattered gravel maintains its original shape.

Mature Reg soils which are Gypsic Haplosalids of *stage E* have developed on Pleistocene surfaces. These profiles have well-developed horizons and the surface is covered by a strongly developed desert pavement. Bar and swale topography is no longer discernible. The B1 horizon is almost entirely gravel-free and the

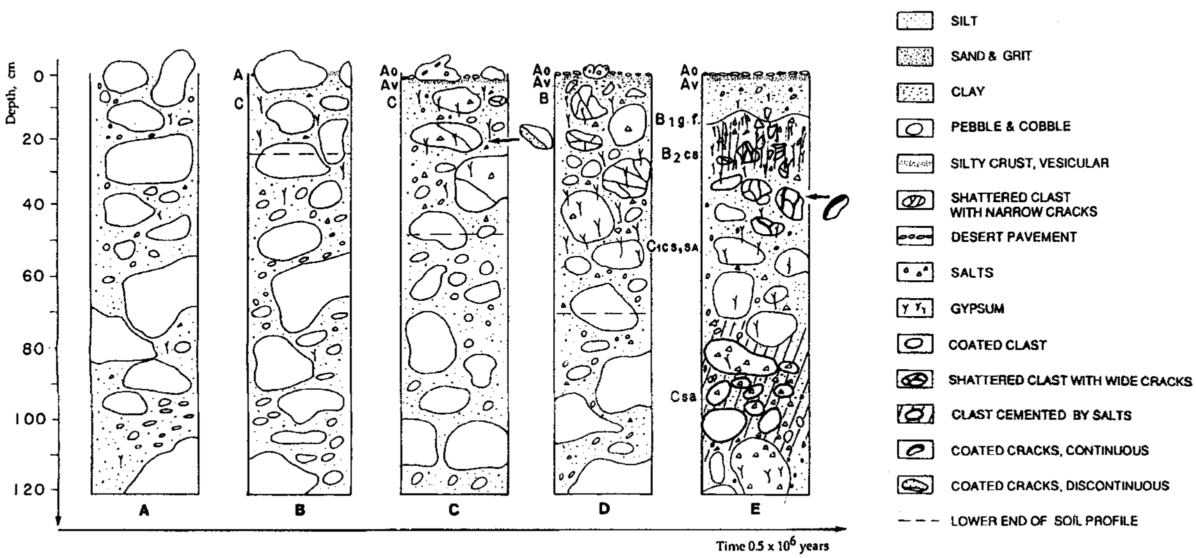


Figure 8. Stages of desert Reg soil development (after Amit *et al.*, 1993). The different crystal forms in the soil profile of each stage are presented in Table II

Figure 9. Upper part of mature Reg soil profile of stage E. Note the alabastrine gypsic horizon

B2cs is gypsic and composed of soft powdery alabastrine gypsum (Figure 9). Salt nodules and salt flakes are distributed in the C1 horizon, while the C2sa horizon is indurated mainly by halite and is defined here as a petrosalic horizon. The highly shattered gravel and its fragments are located in the upper soil horizons from the surface to a depth of 60 cm. Most of the shattered gravel is located in the gypsic horizon at a depth of 20–35 cm.

The salt cutans inside gravel cracks are thick and continuous. They are composed of halite and gypsum together or of each salt separately (Figure 7). Some of them are accompanied by minor amounts of bassanite, anhydrite, and other sulfates such as barite and celestite (Figure 10). Alabastrine gypsum is diagnostic of the

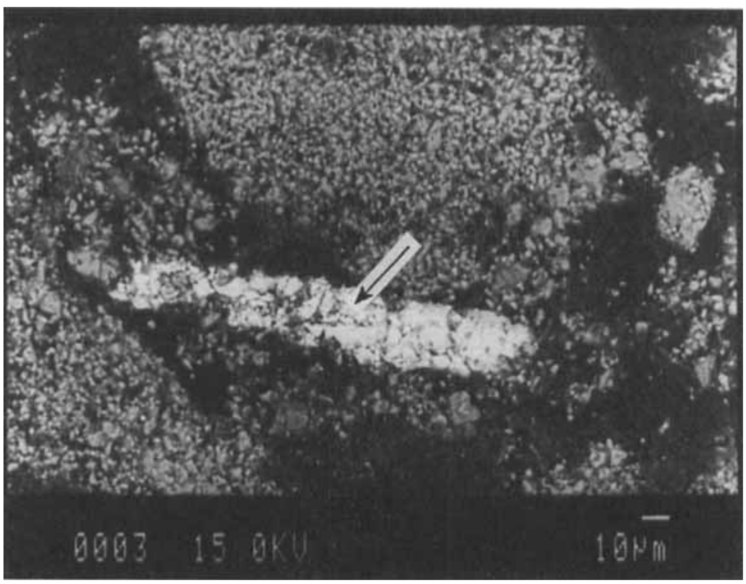


Figure 10. Celestite crystal in the gypsic Bcs horizon (Table I, profile 10, 15–30 cm depth) (electron microprobe)

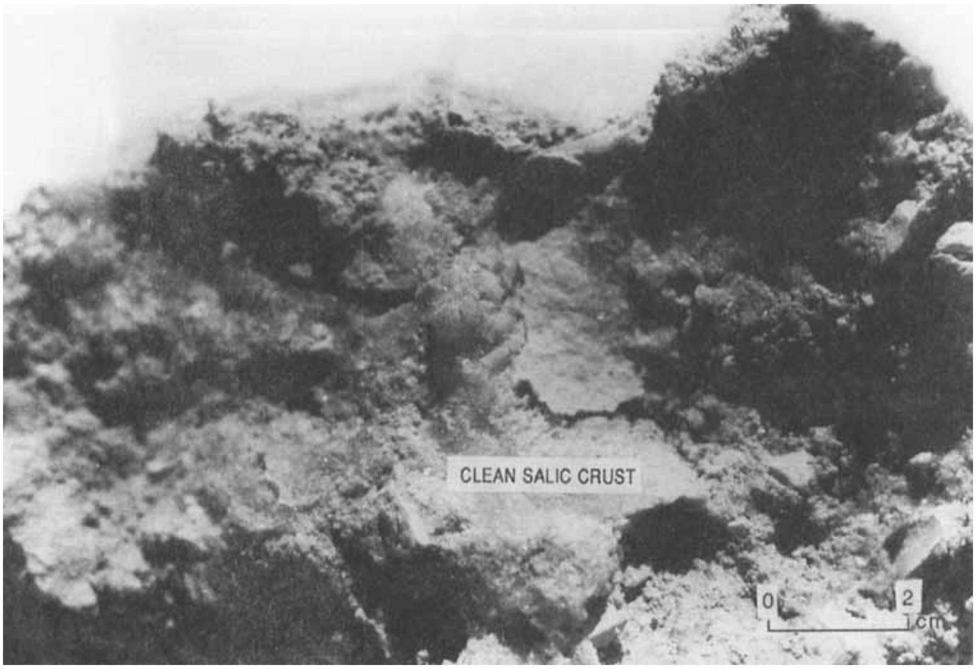


Figure 11. Halite cutans in the petrosalic horizon (Table I, profile 9, 60 cm depth)

upper part of a mature Reg soil. It accumulates mainly in the gypsic B horizon down to a depth of 30 cm, displaces the host material, and is often accompanied by small amounts of prismatic, fibrous and lenticular gypsum crystals (Table II). Halite cubes, which include grains from the host material, are crystallized discontinuously in the soil matrix which was pushed aside by the alabastrine gypsum. Halite crystals containing grains from the host material are very rare in Reg soils and they are characteristic of the Bcs horizon of mature Reg soils of stage E. Below 30 cm lenticular gypsum was found to be more common, with a maximum concentration in the petrosalic horizon (mean depth of 70 cm). The petrosalic horizon is predominantly

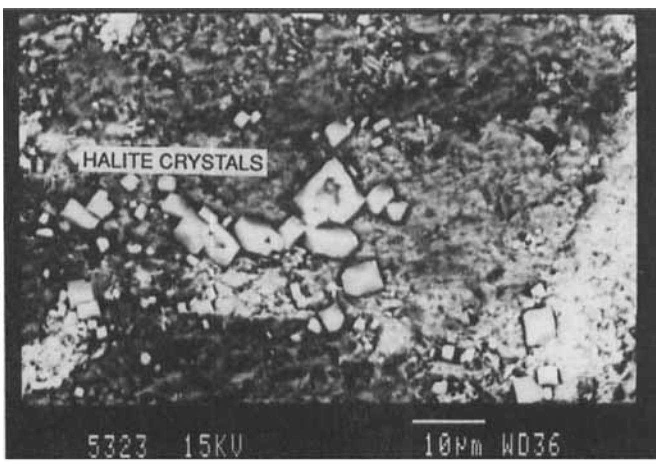


Figure 12. Halite crystals inside gravel in the petrosalic horizon (Table I, profile 10, 70 cm) (SEM)

halite, which was crystallized in contact with the crack planes and with the gravel surfaces forming halan with minor amounts of impurities. The salt cutans inside cracks and around clasts grew in a displacive way (Figures 6a,b and 7) and can attain a thickness of 0·5 cm.

The petrosalic horizon has no shattered gravel (Figure 11) although the pores inside the gravel in the petrosalic horizon are completely filled with salt minerals such as halite (Figure 12), gypsum and minor amounts of calcium chloride crystals. The shattering process, however, does not occur as it does in the uppermost horizons.

DISCUSSION

Factors affecting the formation of gypsum and halite crystal forms in Reg soils

The soluble salts and fine material in Reg soils are thought to be of atmospheric origin (Ericksson, 1958; Yaalon, 1964; Yaalon and Ganor, 1973; Dan and Yaalon, 1982; Babcock *et al.*, 1973; Starinsky and Amitai, 1985; Gerson and Amit, 1987; Amit, 1990; Herut, 1992). The salts accumulate in the soil according to their relative solubility and over time they concentrate at the depth of leaching. The depth of water penetration decreases as the Reg soil develops (Amit *et al.*, 1993). During the initial stages the gravelly soil is very permeable (Figure 8, stages A–C) and water may reach more than 80 cm; in a mature Reg soil it may reach only 10–20 cm (Dan and Yaalon, 1982; Greenbaum, 1986; Amit *et al.*, 1993). In soils of stages A–C, the high roughness of the surface (the bare and swale topography) and the absence of desert pavement allows water and dust penetration (Table I, profiles 1–5) (Gerson and Amit, 1987). The soluble salts are leached deep into the alluvium while the less soluble salts, such as gypsum, tend to be deposited at the mean wetting depth of the soil profile. With time the surface topography changes from bar and swale topography into a smooth desert pavement (Figure 8, stages D and E; Table I, profiles 6–9). Between stages D and E dust continues to accumulate underneath the desert pavement causing a thickening of the B horizon and a change from a gravelly B horizon into a silty, clayey, gravel-free B horizon (Gerson and Amit, 1987; Amit *et al.*, 1993). This results in plugging of the Reg soil surface and a limit to the depth of water and dust penetration (Greenbaum, 1986; Amit *et al.*, 1993). It also affects the temperature regime in the soil (Valentin, 1986). The mean wetting depth in these Reg soils, which already reach stage E, is only 10–20 cm (Greenbaum, 1986). As a result there is a change in the salt distribution along these mature soil profiles over time. These profiles are characterized by two peaks of salt concentrations: a gypsic horizon (Bcs) close to the surface at a mean depth of 20 cm (Bcs horizon), and a petrosalic horizon cemented mainly by halite, at a mean depth of 70 cm (Table I, profiles 8,9). Special attention should be paid to the fact that gypsum and halite are distributed all throughout the Reg profiles and, in non-mature Reg soils, can reach concentrations of at least 10 meq/100 g soil. However, over time, as the dynamic process of soil development continues, the highest concentrations of gypsum and halite, are located at specific depths as a consequence of the varying leaching depth and range of salts solubility (Amit *et al.*, 1993).

One of the interesting aspects of the gypsum in Reg soils is the fact that in a single profile it is possible to find several kinds of gypsum crystal forms. The variety of forms includes fibrous crystals, lenses, prismatic crystals and alabastrine gypsic crystals. Lenticular gypsum has been described in a wide range of environments: in arid soils, in coastal lake salinas and in continental playas (Hanna and Stoops, 1976; Barzanji and Stoops, 1974; Warren and Kendall; 1985; Rosen and Warren, 1990; Amit *et al.*, 1993). In Reg soils it is common in all stages (Table I, Figure 8). In young, permeable, Holocene Reg soils (Table I, profiles 2–7, Table II) poikilitic gypsum lenses are distributed from the surface to a depth of 50 cm accompanied by minor amounts of prismatic gypsum crystals. In mature, sealed Reg soil profiles (Table I, profiles 8–9, Table II), the lenticular gypsum is distributed throughout the profile but the highest amount of gypsum lenses are found in the petrosalic horizon (Table II).

Two major processes have been proposed for crystallization of lenticular gypsum: ion impurities within the soil solution (Kushnir, 1980; Edinger, 1973; Franchini and Rinaudo, 1989) or crystallization in a void system where space is not limiting (Eswaran and Gong, 1991). Preferential absorbance of different ions has been shown to produce lenticular gypsum (Edinger, 1973; Kushnir, 1980) and increased NaCl content

can cause a decrease in the nucleation density and production of lenticular crystals (Cody and Cody, 1988). In highly permeable Reg soils at stages A–D (Table I, profiles 1–7), gypsum crystallizes in voids. In addition, the high permeability allows high evaporation rates to 50 cm depth (Amit *et al.*, 1993). Under such conditions, the impure saline solution which concentrates around gravel or inside cracks of the shattered gravel can produce lenticular gypsum. Mature Reg soils (Table I, profiles 8,9) have high concentrations of NaCl throughout the soil. The highest concentration of lenses was found in the petrosalic horizons which contain 750–800 meq/100 g soil NaCl. The halite impurity may be the reason for the deposition of lenticular gypsum (Cody and Cody, 1988) in the mature soil profiles in general, and in the petrosalic horizon in particular.

Deposition of alabastrine gypsum is restricted to mature Reg soils in which the upper horizons are plugged, limiting the depth of leaching (Table I, profiles 8,9). Evaporation rates are also higher close to the surface. Under such conditions supersaturated saline solutions are produced and deposition of alabastrine gypsum can occur (Edinger, 1973; Cody, 1979; Watson, 1988).

Prismatic gypsum is rarely reported in arid soils (Jafarzadeh and Burnham, 1992) but is frequent in lacustrine environments (Rosen and Warren, 1990). In the Reg soils, minor amounts of this crystal form are found throughout young profiles and in the lower parts of mature profiles associated with lenticular gypsum. Although it has been described as forming under acid conditions (pH values of 4–6) (Jafrzadeh and Burnham, 1992), such conditions do not occur in Reg soils. This form grows mostly in sediment-free solutions such as bottom nucleated brine-pond gypsum at the sediment–water interface and as free crystals at the brine–air interface (Cody and Shanks, 1974; Cody, 1976; Rosen and Warren, 1990). In addition, their form can be a result of selective adsorption of H and OH on 110 and 010 faces of the crystals (Edinger, 1973) or as a result of evaporation of solutions saturated with gypsum but with no organic matter (Cody, 1979). Such conditions can exist locally in the gravelly Reg soil.

Fibrous gypsum crystals are not common in Reg soils and in desert soils in general. They were found in this study only in mature profiles at depth of 35–45 cm in which shattered gravel were re-cemented by salts (Amit *et al.*, 1993). Jafarzadeh and Burnham (1992) stress that the limited space to expand is a key factor for this crystal form to occur. These crystals are found inside re-cemented shattered gravel, which suggests that crystallization in a confined space enhances the growth of this crystal form.

Owing to its high solubility, halite may not remain continuously in a crystalline state in soils, and in addition the mineral is often lost during thin section preparation (Eswaran *et al.*, 1980). In all Reg soils, however, halite cutans are well-preserved and are composed of pure cubic crystals which displace the host material. In the gypsic horizon, B2cs halite is found within the displaced soil matrix as dispersed cubes. These crystals are not pure and include grains from the host material. This indicates deposition during the last stages of crystallization from a saline soil solution, supersaturated with respect to gypsum, and the influence of high evaporation rates close to the soil surface (Eswaran *et al.*, 1980). Such conditions prevail in mature Reg soils of stage E. The halans around the gravel in the petrosalic horizons and the salts deposited inside the gravel in this horizon are continuous and composed of euhedral cubic crystals. They are not in the form of a diffuse waxy coating, reported by Eswaran *et al.* (1980) as being the only form recorded in salic horizons (Driessen, 1970; Hanna and Stoops, 1976).

Possible relation between the gravel-shattering process and halite and gypsum crystal forms

Halite and gypsum crystallize both displacively and passively. The gypsum which crystallizes in a displacive way is mainly the alabastrine gypsum. Prismatic gypsum in young and mature profiles and the acicular gypsum in mature Reg soils also crystallize displacively but they are minor components in these soils. The lenticular gypsum which characterizes the young and mature soils crystallizes passively.

Displacive or passive deposition probably reflects the type of bonding between the cement compounds (Chadwick and Nettleton, 1990). Covalent bonding favours adhesion of the cementing compounds to the existing soil matrix which results in close-porphyric fabric, isotic plasma and passive precipitation. In contrast, ionic bonding favours cohesion of the cementing agent to itself which results in open-porphyric and crystic plasma. As a result, cementation occurs as crystals cohere to each other through chemical intergrowth and physical interlocking. The soil matrix is not held in place by cohesion and is displaced by the increasing

Figure 13. Petrosalic horizon (Csa) in mature Reg soil of stage E at a depth of 70 cm. Note the non-shattered gravel and the enveloping salic crusts

pressure and volume of the crystic plasma. In addition, the presence of supersaturated solutions and the surface free energy have also been suggested as important factors for displacive crystallization of minerals (Kastner, 1970; Weyl, 1959; Carstens, 1986).

No correlation was found between the occurrence of shattered gravel and the occurrence of displacive halite and gypsum crystals in soil profiles. Shattered gravel in young and mature Reg soils is found from the surface to a depth of 45–50 cm. At a depth of 0–45 cm, particularly in the mature soil profiles, the gypsum is mainly alabastrine gypsum and shattered fragments are displaced by these gypsum crystals (Figures 3 and 7). However, in young soil profiles there is a very small amount of gypsum which grows displacively, though there is still a significant amount of shattered gravel. Moreover, in the lower parts of mature profiles, below the horizon of the shattered gravel, displacive gypsum was found but without shattered gravel. Hence displacive growth does not necessarily mean shattering. Similarly halite, which characterizes the petrosalic horizon, is deposited in a displacive way but no shattered gravel is found in this horizon (Figure 13) although halite crystals were crystallized inside gravel (Figure 12). It seems that the displacive process can enhance the gravel-shattering process but cannot be the sole or main factor for this process. As reported by Winkler and Wilhelm (1970), Winkler and Singer (1972), and Ravina and Zaslavsky (1974), salt crystals exert high stresses during their growth, particularly through the hydration process. These stress rates even exceed that required for gravel shattering (Amit *et al.*, 1993). None of these studies discusses the implication of the different crystal forms on the salt-weathering process. Sperling and Cooke (1980) emphasize the relation between rate of the salt weathering process and the crystallographic characteristics of the different salts involved in this process. More work is needed in order to understand the possible correlation between crystal form, crystallization and the pressure which it exerts in the soil matrix, both in gravel cracks and in microcracks.

CONCLUSIONS

Holocene and Pleistocene Reg soils (Haplogypsids and Haplosalids) are characterized by a variety of gypsum and halite crystal forms although they are well-drained and are unaffected by high water table conditions. Deposition of poikilitic lenticular gypsum will occur when saline solutions have ionic impurities

or when the crystallization of the gypsum is in a void system such as gravelly alluvium with low amounts of fine material.

In mature Reg soils, which are plugged by the accumulation of dust close to the surface and by the desert pavement, the wetting and leaching depth is limited to the upper 10 to 20 cm. As a result, alabastrine powdery gypsum is deposited. These gypsum crystals indicate a frequent a high degree of supersaturation and a high degree of evaporation in the upper parts of the soil profile.

Changes in crystal forms of gypsum in Reg soils reflect the microenvironmental changes in the soil profile during its development over time. The transition from lenticular to alabastrine gypsum accumulation is a result of crossing an intrinsic threshold in soil development. The build-up in fines and the increasing development of desert pavement gradually reduces the depth of water penetration in the soil and enhances the degree of evaporation producing conditions conducive to precipitation of alabastrine gypsum.

The lack of correlation between the chemical type and amount of salt and between displacive crystal growth and the degree of salt shattering, suggests that other factors determine the location and amount of salt shattering.

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